Experimental Evidence for Super-resolution in the Spherical Geodesic Waveguide

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***Abstract* – The previous publications (Miñano et al, 2011 and Gonzalez et al, 2012) have shown that using a Spherical Geodesic Waveguide (SGW) it can be achieved the super-resolution up to λ /3000, which is far below the classic Abbe diffraction limit, close to a set of discrete microwave frequencies. The SGW was designed and simulated in COMSOL as a thin geodesic waveguide bounded by an ideal and lossless metal. Herein we present the experimental results for a manufactured SGW, slightly modified due to fabrication requirements, showing the super-resolution up to λ /105.**

I. INTRODUCTION

In 2009 Leonhardt [1] analyzed TE-polarized wave fields in the MFE lens in two dimensions (2D). Leonhardt found a family of Helmholtz wave fields which have a monopole asymptotic behavior at an object point as well as at its stigmatic image point. Each one of these solutions describes a wave propagating from the object point to the image point. This wave coincides asymptotically with an outward (monopole) Helmholtz wave at the object point, as generated by a point source, and with an inward (monopole) wave at the image point, as it was sunk by an "infinitely-well localized drain" (called Perfect Point Drain PPD). This PPD absorbs the incident wave, with no reflection or scattering. In [2] it has been proved that the PPD can be modeled as a small dissipative region with a properly calculated complex permittivity which depends on frequency. Leonhardt assumed that the ability of the MFE to propagate the wave, generated by a point source, toward to a PPD was enough to guarantee perfect imaging. This does not seem to be sufficient, since it does not provide information on how much power this drain will absorb when it is displaced out of the image point. One experiment was recently carried out to support the super-resolution (SR) capability in the MFE for one microwave frequency [3]. The results showed that two sources with a distance of λ/5 from each other could be resolved, which exceeded the ~λ/2.5 classic diffraction limit. It is interesting to note that in this experiment the receptor is not the PPD but only a coaxial probe loaded with its characteristics impedance.

In 2010 Miñano demonstrated using Transformation Optics [4] that all the results shown by the MFE can be translated to a novel device more practical for manufacturing, the Spherical Geodesic Waveguide (the SGW). In 2011 Miñano published another paper [5] showing by simulation in COMSOL that in the SGW it can be reached the SR up to λ /500 near to some specific set of microwave frequencies. The port and drain have been realized using the coaxial probes (without using the PPD). In 2012 Gonzalez explained a circuital model for perfect drain (the PPD is realized using simple elements such as resistance and capacitor), which is connected at the drain coaxial probe of the SGW [6]. The existence of the PPD increased the SR up to λ /3000.

II. MODEL DESCRIPTION

The SGW is bounded by two aluminum spherical shells. Although the refractive index media should be $1/r$, r being the radial coordinate, since the spherical shells are close compared to their size, using air as media in between shells is such a good approximation [5]. Fig. 1 presents the scheme of the manufactured SGW. The source and drain are realized using the coaxial cables. The source is fixed, while the drain is connected with a moveable slider. The source and drain are much smaller than the SGW, hence they can be considered as a good approximation of the point source and drain. The SGW dimensions are R_{max} = 150 mm, R_{min} = 145 mm (which is 6 times smaller than the SGW from [5], [6], while the thickness remains the same 5 mm), D_i =1.3 mm (diameter of the inner coaxial line), D_e=4.1 mm (diameter of the outer coaxial line), L=10 mm.

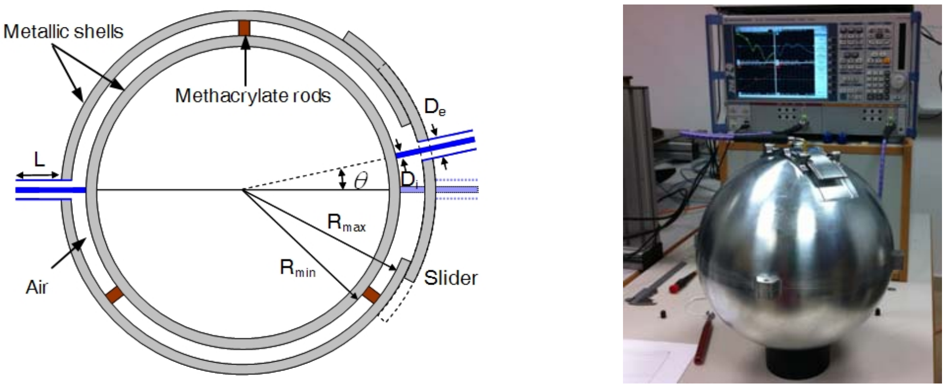


Fig. 1. Schematic presentation of the SGW with coaxial cables. The slider is moving smoothly on the outer sphere to tilt the drain. Methacrylate rods serve for holding the inner metallic shell (left). Experimental setup, the manufactured SGW is connected to the Vector Network Analyzer (right)

III. EXPERIMENTAL RESULTS

To calculate the transmitted power from the source to the drain for different positions of the drain we have used the scattering (S) parameters. The Scattering parameters were measured directly using a Vector Network Analyzer as shown in Fig. 1. The SGW is analyzed using the frequencies in the range from 1 GHz to 1.3 GHz (the wavelength varies from 300 to 230 mm respectively). At first we put the slider at θ=0 in order to have the detector at the image point, then, the drain port is shifted by λ/N (λ=268.2 mm, being the wavelength corresponding to a local minimum of the transmitted power at 1.1184 GH_z, see Fig. 2) from the image point. The change in the transmitted power is defined using the parameter $M=Pt_\theta/Pt_{\theta=0}$, where $Pt_{\theta=0}$ is the trasmitted power when the drain is placed at θ=0, while Pt_θ is the transmitted power in the case when the drain is shifted.

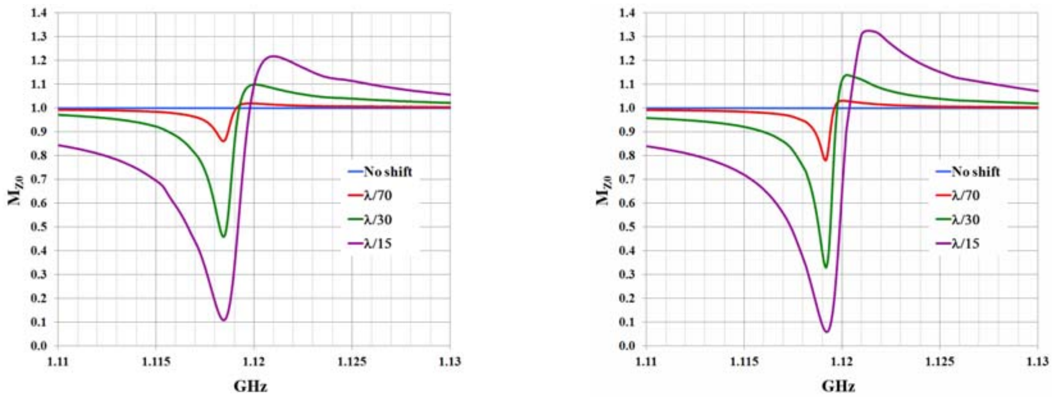
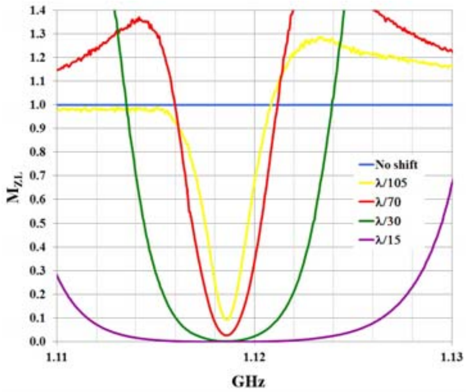


Fig. 2. The parameter M obtained experimentally (left) and in COMSOL (right) as a function of the frequency for different positions of the drain when $Z_L=Z_g=Z_0=50\Omega$. The blue line shows the case when there is no shift, while the red, green and violet shows the shifts λ/70, λ/30 and λ/15

Consider a microwave circuit containing the SGW, a generator Vg=1V with impedance $Z_g=Z_0$ (characteristics impedance of the coaxial line $Z_0=50\Omega$) on the source side of the SGW, and the load with impedance $Z_L=Z_0$ on the drain side. The same scheme was proposed in [6]. Fig. 2 shows the experimental and simulation (done in COMSOL) results for the parameter M. In both charts one can see the sudden drop in the transmitted power (in the case when the drain is shifted from θ=0) at a certain frequency called notch frequency. This means that our receiver senses a small shift, which is smaller than the wavelength. Let us define "resolution" as the arc length (in wavelength units) that a drain port needs to be shifted so the transmitted power drops to 10% of the transmitted power when there is no shift, i.e. M is equal to 0.1. According the experiment it happens at the notch frequency when the drain is shifted by λ/15, while the simulations predict a slightly bigger resolution λ/18.



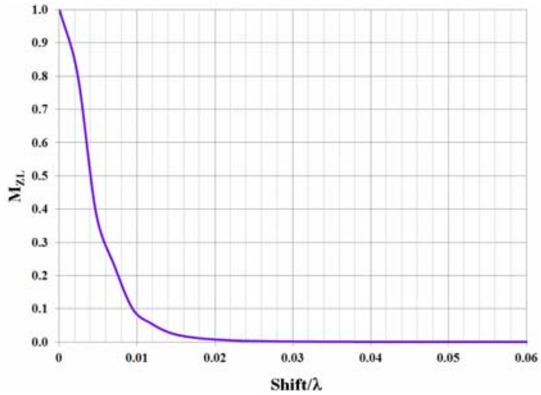


Fig. 3 The case when Z_L and Z_g maximize the SR. The parameter M obtained experimentally as a function of the frequency for different shifts (left). The parameter M obtained experimentally as a function of the drain position at the notch frequency

Using measured S parameters from the experiment, there are calculated the impedances of the load and the generator that maximize the SR. The highest SR up to λ/105 has been achieved using a complex impedance Z_g (realized with a resistance 9.77Ω and a capacitor of 0.62 pF) on the source side of the SGW, and a complex impedance Z_L (realized with a resistance of 0.4 Ω and a capacitor of 1.78 pF) on the drain side. Fig. 3 shows the change in transmitted power as a function of the frequency close to the notch frequency for different drain positions. The right side of Fig. 3 shows how the parameter M decreases as the drain is moving away from the image point at the notch frequency. The parameter M reaches the value 0.1 when the drain is shifted by λ/105, which is resolution of the system.

IV. Conclusion

The experimental measurements of the first manufactured SGW have confirmed the super-resolution properties of the device, showing the resolution up to λ/105. The similarity between the experiment and the COMSOL simulation confirms the precision of the measurements. The use of real metallic material for the shells (it has been shown in COMSOL that when the conductivity decreases the SR decreases as well), dropped the SR, thus the measured SR is lower than in ideal cases reported in [5] and [6].

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